



Some Nb₃Sn Magnet Test Failures and Some Lessons-Learned at LBNL

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LBNL Superconducting Magnet Testing

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Introduction

- Magnet Failure:
 - inadequate or unexpected performance.
- Some examples & lessons learned.
- Summary
- Future Plans



Mission

LBL Superconducting Magnet Group:

- Develop magnet technology for cost-effective, high-field accelerator options.
- Design & fabricate POP coils and magnets.

Superconducting Magnet Test Facility:

- Determine performance of POP magnets.
- Generate feedback for design/fabrication teams.



Hardware: PS's & Cryostats

Power Supplies:

- 21kA (3*7kA, 2 T-lines)
- 12kA (energy extraction)

Cryostats:

1. 36" horizontal 1.8K
2. 32" vertical 4.3K
3. 15" vertical 4.3K



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Hardware: DAQ Limitations

Continuous History (2-300s/sample):

- Cryostat: 20 chn (4-wire) + 20 chn (2-wire)
- S-gauge: 20 chn (2-wire)

Ramp History (0.5-6s/sample):

- Primary: 40 chn (2-wire, S-gauge & Rsplice)
- S-gauge back-up: 20 chn (2-wire)

Quench (0.2-5 K-samples/s):

- 96 chns (QDC triggered)

Fast-Flux (50-200 K-samples/s):

- 4 chns (imbalance triggered)



Hardware: Magnetic Measurement

Rotating coils (tangential + D&Q bucking):

1. $L = 43$ cm $r = 1.2$ cm (needs repair)
2. $L = 100$ cm $r = 1.2$ cm (needs repair)
3. $L = 10$ cm $r = 1.2$ cm (FNAL loan)
4. $L = 80$ cm $r = 2.4$ cm (FNAL loan)

Measurement Benches:

1. Horizontal: ~ 4 meter scan
2. Vertical: ~ 1.5 meter scan

Anti-cryostats:

1. 35mm OD 25mm ID
2. 63mm OD 50mm ID



LBL Nb₃Sn Magnet “Failures”

D20 (1997, 13T, 50mm, 4-coil, cos-theta dipole):

- ~95% of 1.8K Iss.
- Degraded: 13.5T to 12T @ 1.8K. (< 4.3K Iss).
- Movement of low-field splice.
- Recovered 4.3K Iss on 2nd thermal cycle (12.8T) .
- a₂ hysteresis.

RD3a (2000): 14.5T, 10mm, common-coil dipole.

- Internal arc on first quench (~60% of Iss).
- Careless insulation between coil, heater & metallic coil-case.
- Voltage aggravated by mismatched quenching L/R's .
- Destroyed two of the three coils.



LBL Nb₃Sn Magnet “Failures”

SM02 (Feb. 2002): 12T, small, mixed-strand common-coil dipole.

- ~40% of I_{ss} (mystery remains).

RD3c (May 2002): 11T, 35mm, 3-coil, common-coil dipole:

- ~95% of I_{ss} (repeated conductor motions).
- 5 unit shift in sextupole.
- b₂ hysteresis (left-right asymmetry in D_{eff})

SM03 (Oct. 2002): 12T, small cored mixed-strand common-coil:

- 65% of I_{ss}, consistent splice quenching.
- Damaged conductor near splice.

NMR (July 2003): 11T, small 4-coil opposed common-coil:

- 60% of I_{ss} (mystery remains).

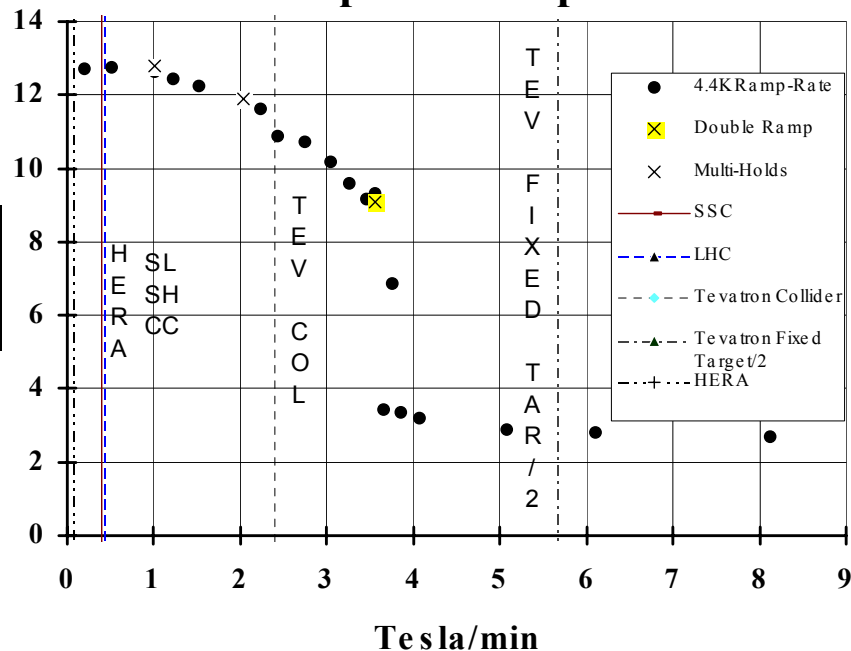


D20

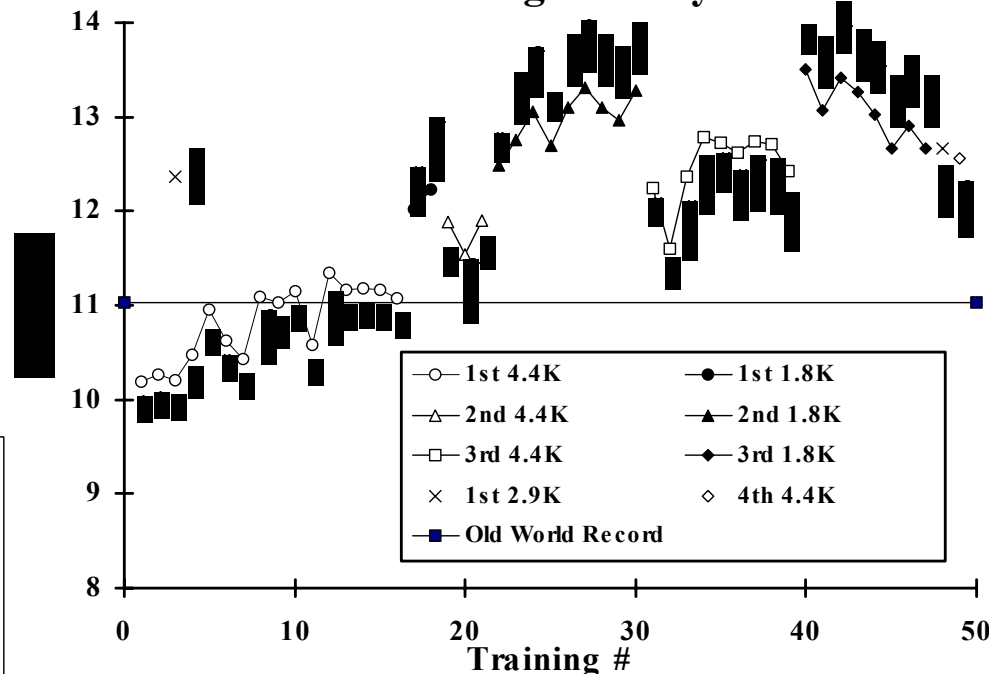
Performance:

- 13.5T, but costly & slow.
- Ramp-rate cliff.

D20: Ramp-Rate Dependence



D20: Training History



Lessons:

- Need better, safer pre-stress.
- Better splice immobilization.
- More smaller magnet tests.
- Ramp-rate cliff: quench-back.



D20: MagMeas

Measurement Interest:

- Geometric Harmonics
- Axial & current dependence
- Hysteresis.

Disappointments:

- Large hysteresis
- $a_2 > b_3$
- $a_2 = -6 \times 10^{-4}$ (upramp)

Lessons:

- D_{eff} needs to be smaller (or compensated)
- D_{eff} needs to be balanced between coils.

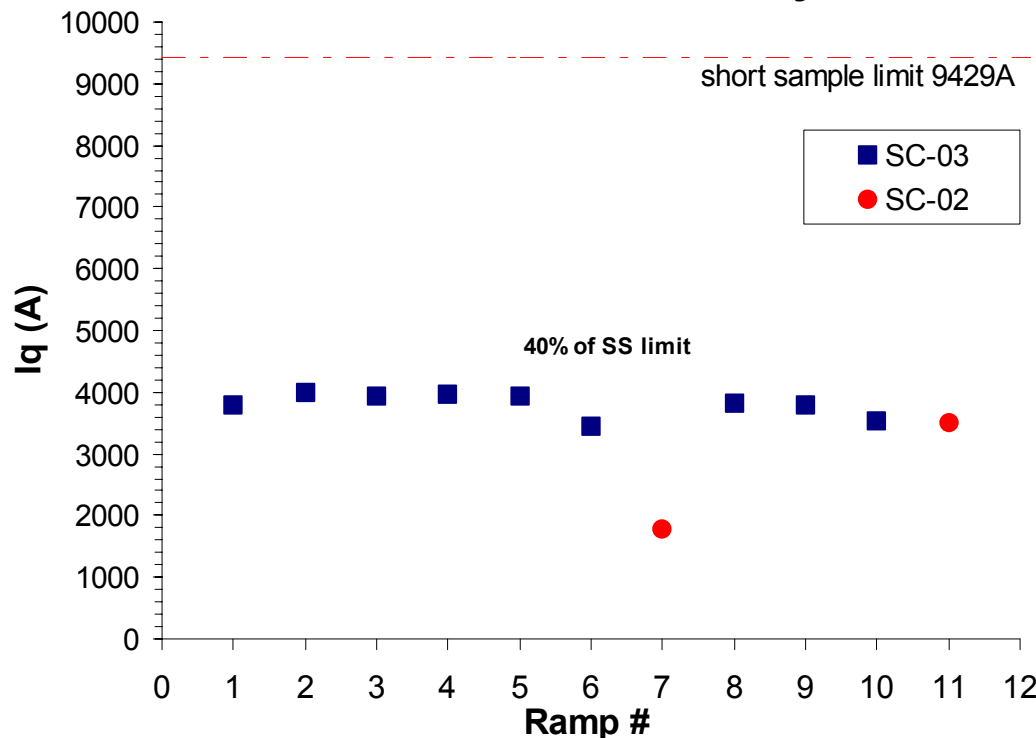


SM-02

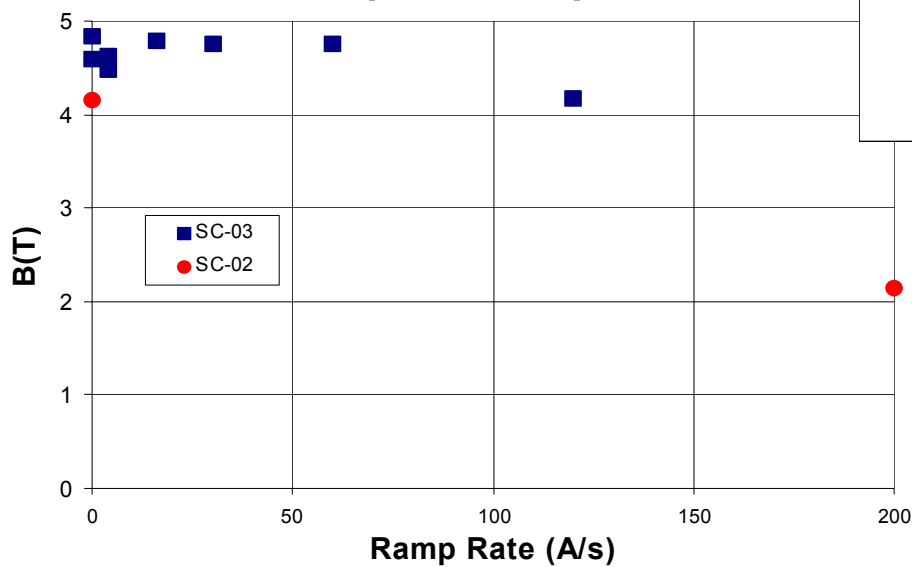
Performance:

- $RRR = 250$
- 4.8T (40% of SS-limit)
- No ramp-rate hump.
- Splice quenching?? (noise).

SM-02 Quench History



SM-02 Ramp Rate Dependence



Lessons:

- Higher S/N for high RRR splices.

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RD3c: Harmonic Measurement Goals

First “Common-Coil” harmonic measurements:

- Design: $\sim 10^{-4}$ central dipole harmonics @ max.B.
- Measure relevant geometric & dynamic effects.
- Compare with calculations.

Cost constraints:

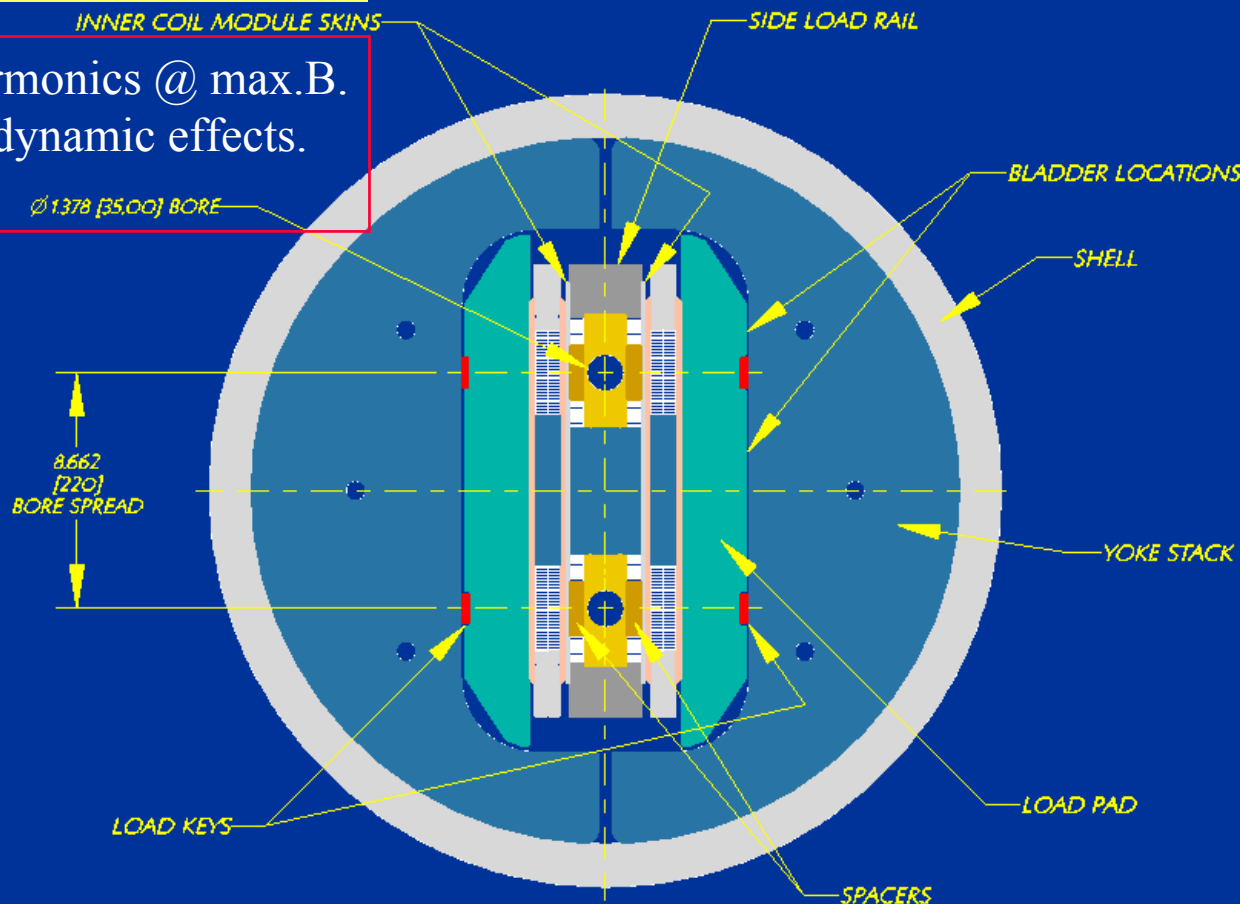
- Reuse RD3b outer coils.
- Reuse RD3b yoke/structure.
- New, RD3b-style harmonic correction coil-module.

Correction-coil restraints:

- One-layer/side.
- One spacer/layer/bore.

Bore constraints:

- 35mm bore (10.9 T)

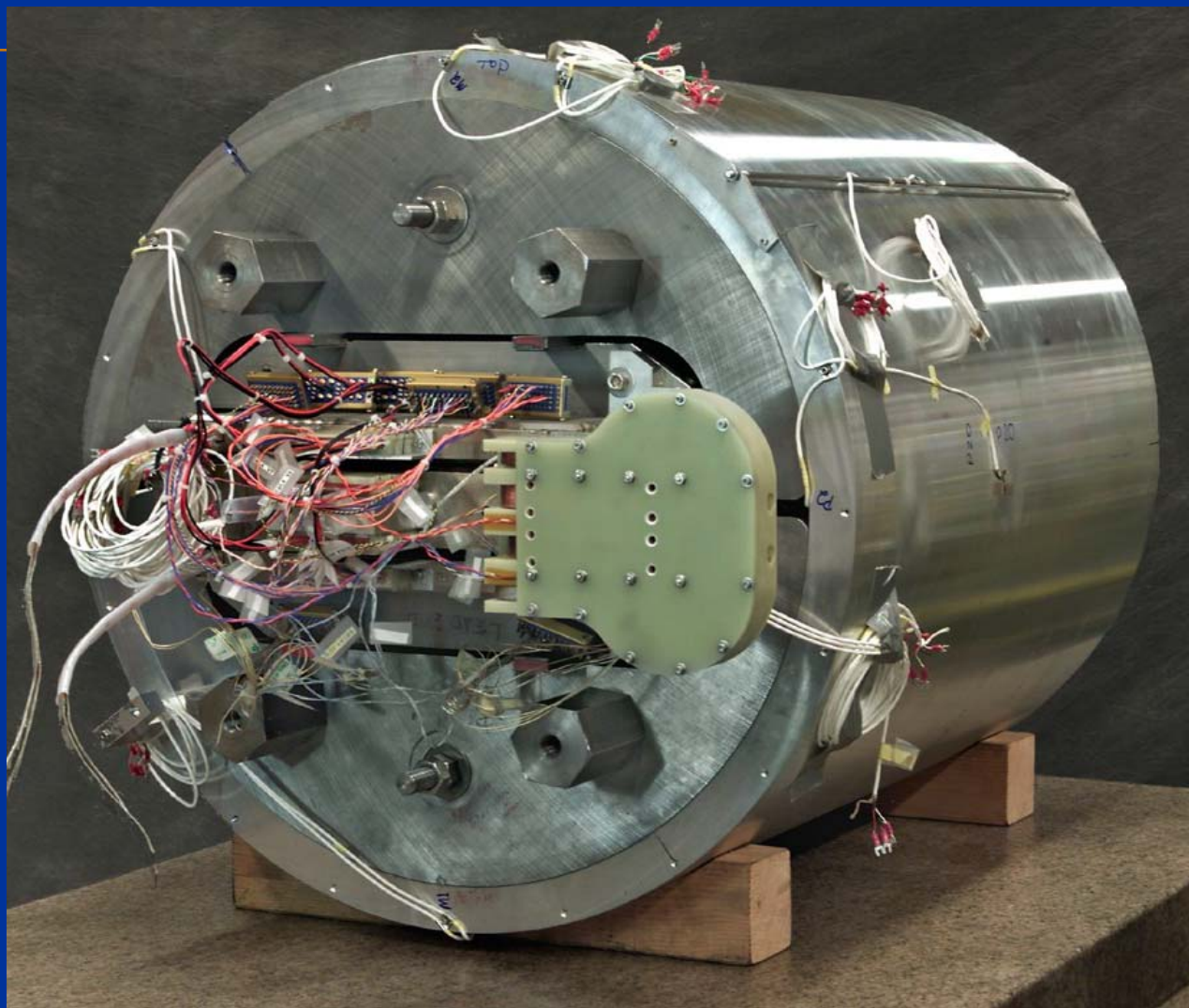




RD3c: 11T Racetrack Common-Coil

Cost-Effective:

- Reuse 16T structure:
 - Iron yoke
 - Bladder & Key
 - Al shell
- Reuse 14.5T outer coils.



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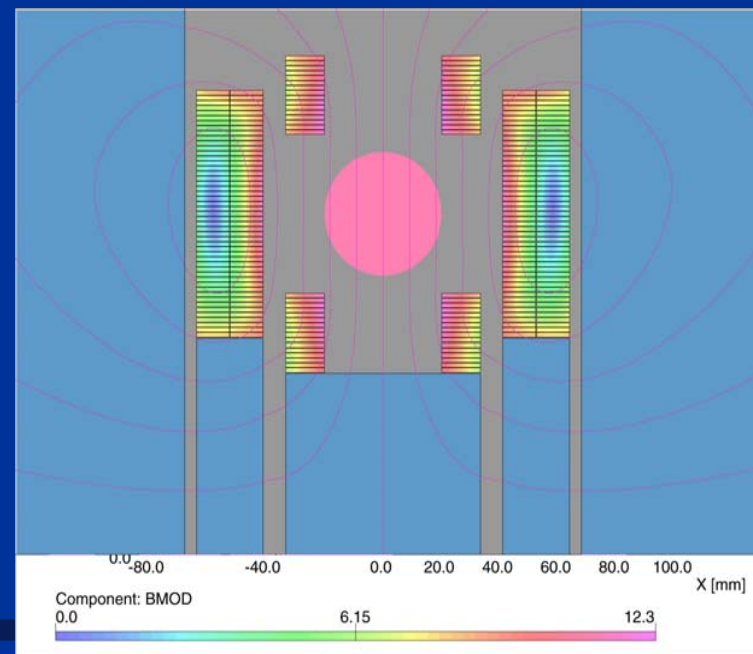
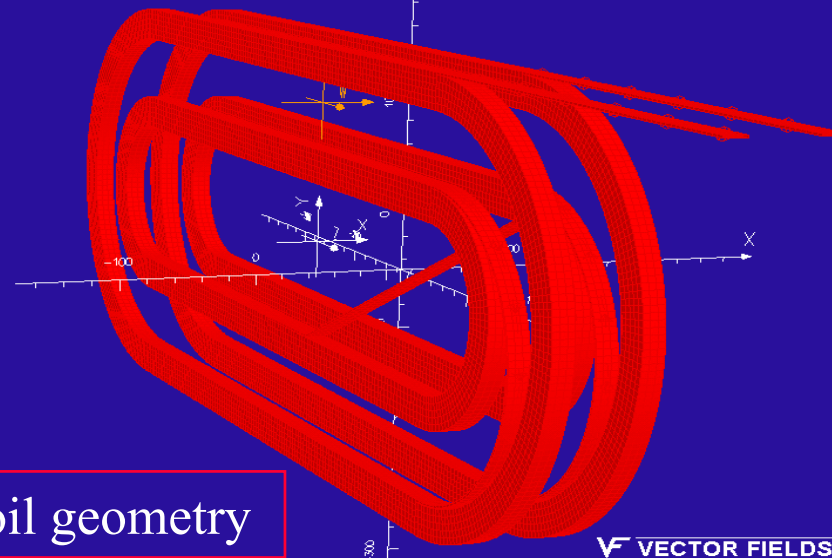


RD3c: Magnetic Design

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Challenge:

- Correct large positive sextupole (reused outer coils).
- Large (a2) quadrupole (reused yoke).
- Large SC-hysteresis (Nb_3Sn)
- Smallest possible bore.



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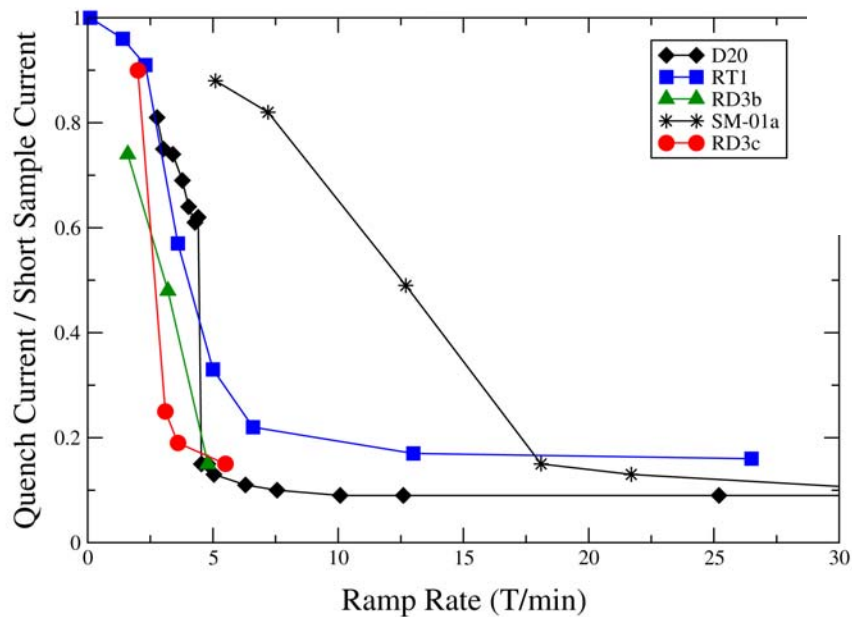


RD3c

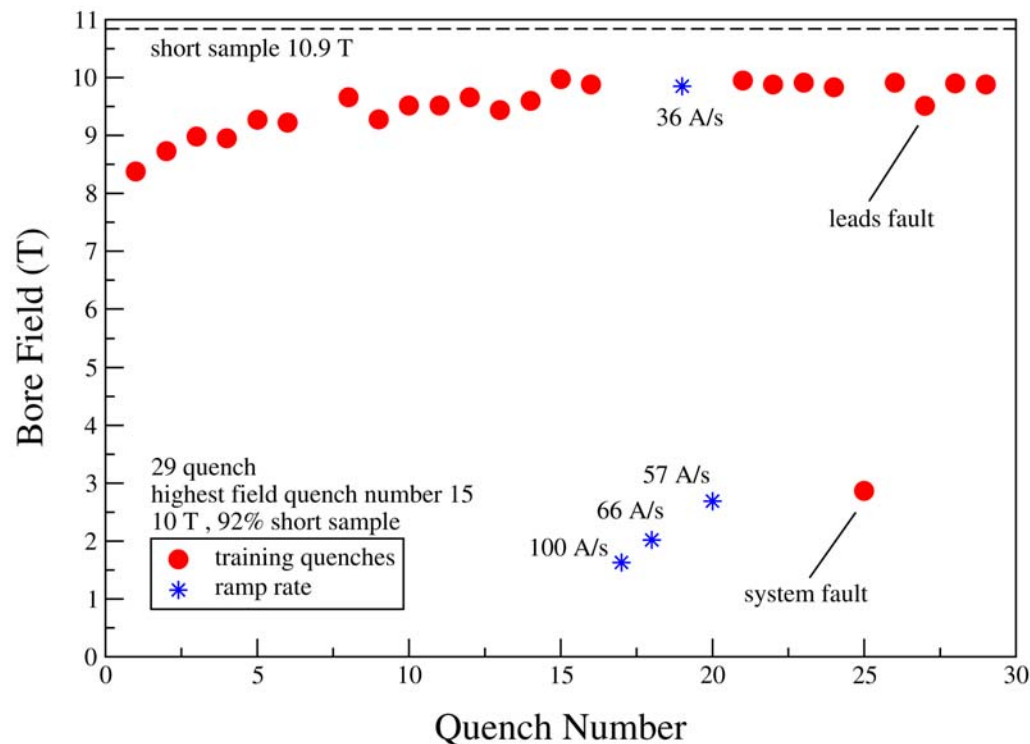
Magnet Performance:

- ~90% of SS-limit
- Slow training, aborted.
- Usual ramp-rate cliff.

RAMP RATE SENSITIVITY



QUENCH HISTORY RD3c



Conductor/splice performance:

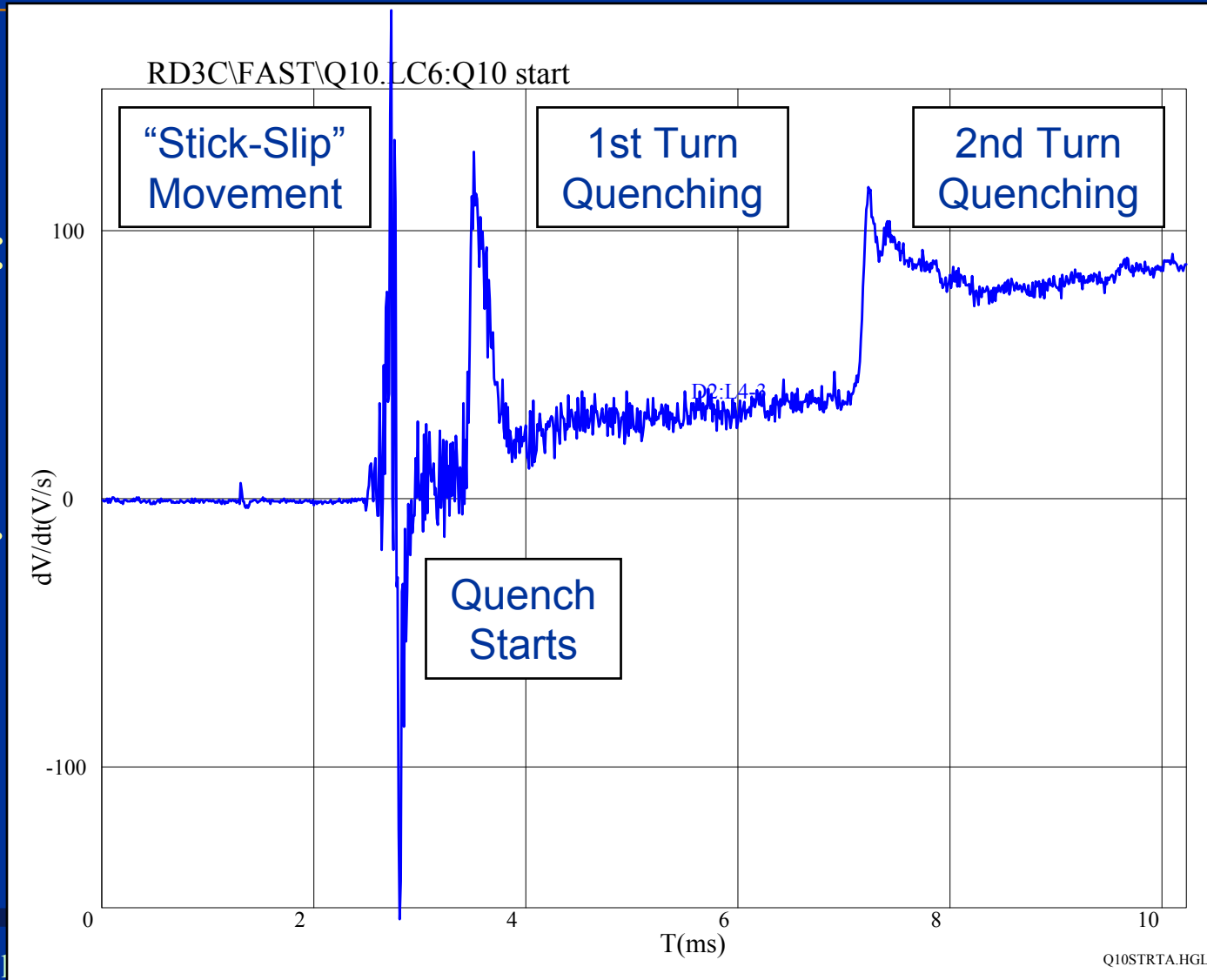
- RRR = better balanced
- $R_{splice} < 1 \text{ nOhm}$
- Flux jumps at low current.
- Repeating conductor movement.

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RD3c: “Stick-Slip” Quench Triggers

- HF Impulse:
 - 300V/s
 - >2000V/s
- HF Ringing.
- Occasional quench trigger.

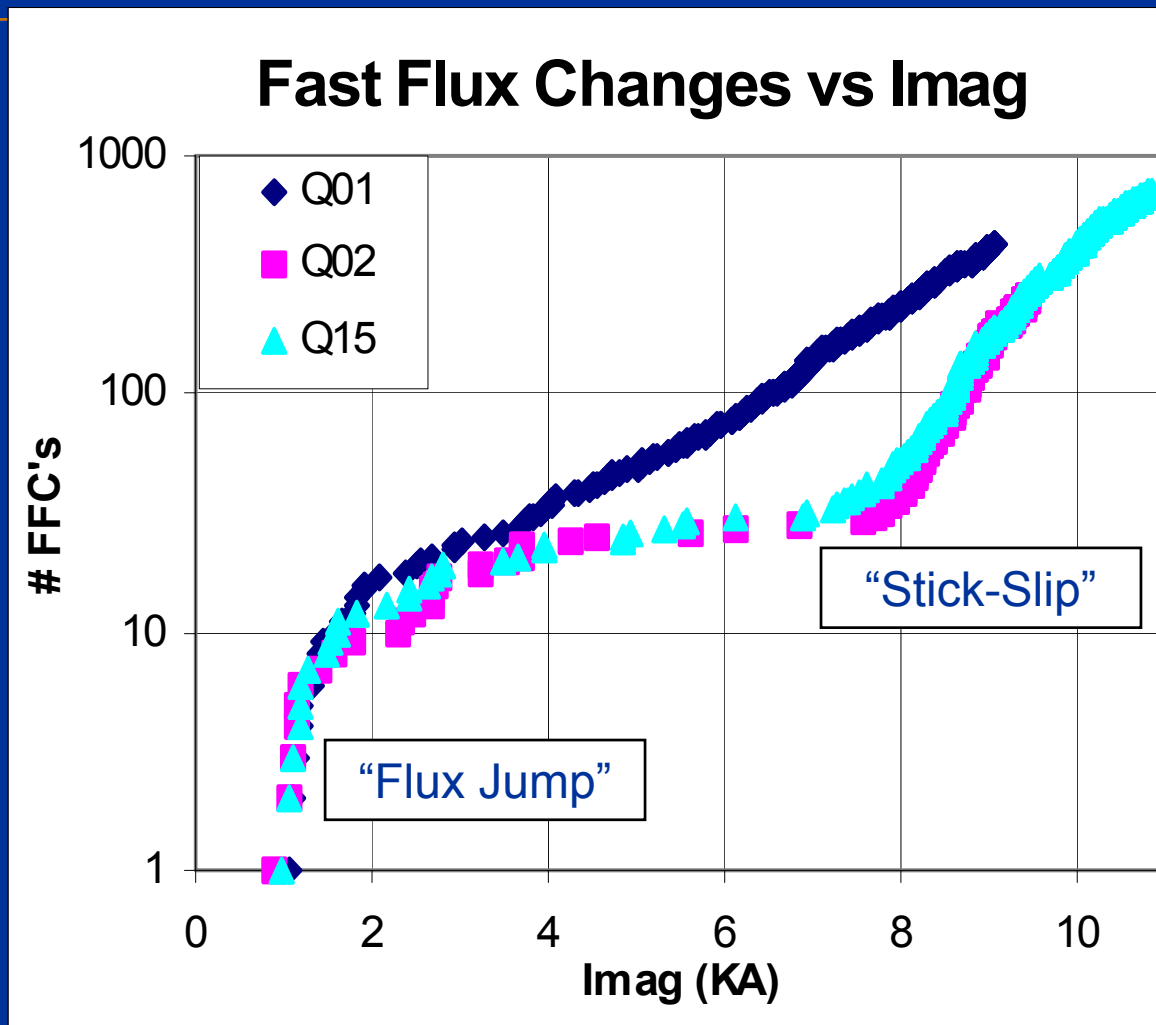




RD3c: Fast Flux Adjustments

Two Kinds:

- “Flux Jumps”:
 - Slow (10ms)
 - $I < 50\%$ of I_{ss}
 - Polarity $\sim dB/dt$.
 - Every ramp.
- “Stick-Slip”:
 - Fast (0.1ms)
 - “Training”:
 - Yes $< 8\text{KA}$.
 - No $> 8\text{KA}$.

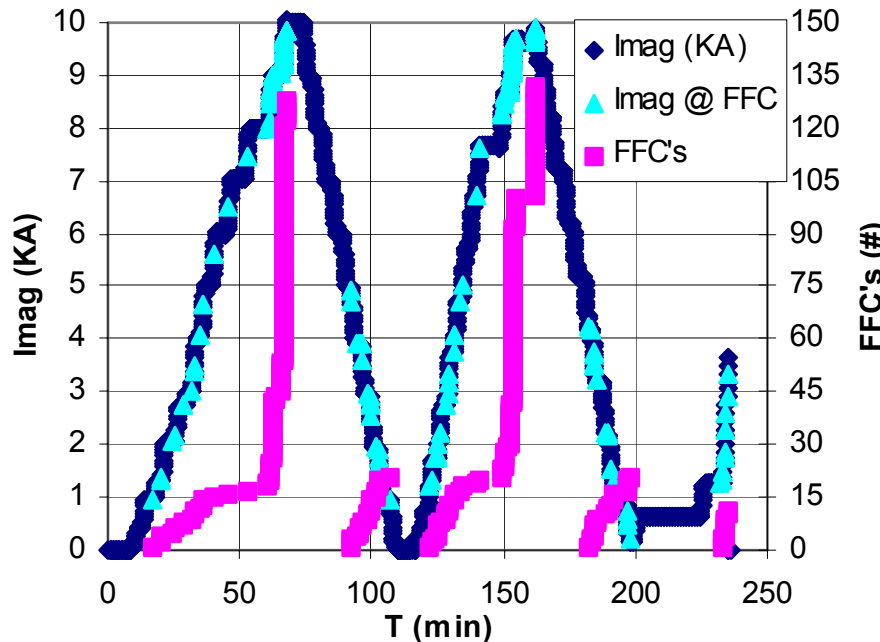


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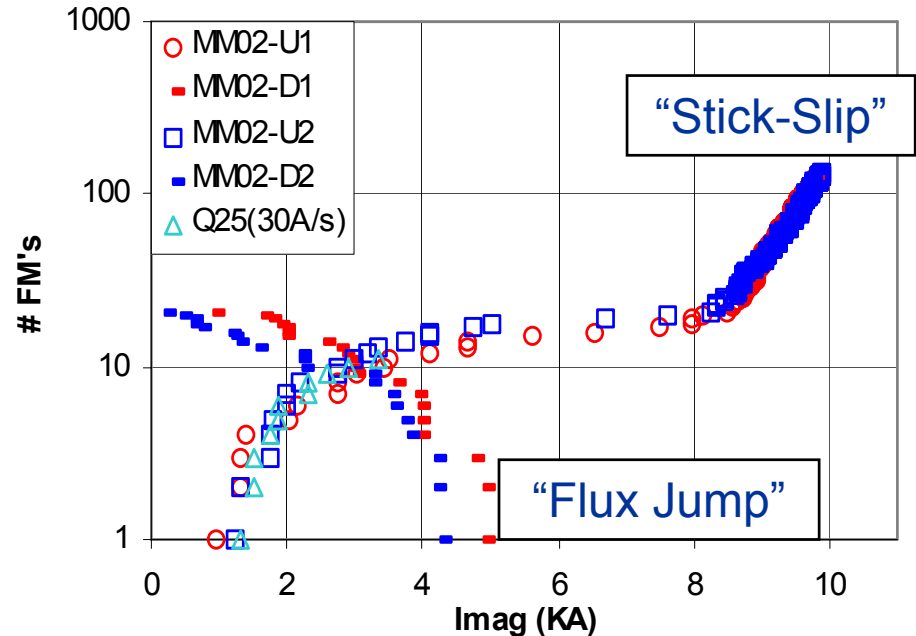


RD3c: Multi-Ramp FFC “Training”

M02: Fast Flux Change History



MM02 Fast Flux Changes vs. Imag



- “Flux Jump”: Repeat on down-ramp.
- “Stick-Slip”:
 - Only with up-ramp (threshold = 300V/s).
 - Repeat (forget) $> 8\text{KA}$.

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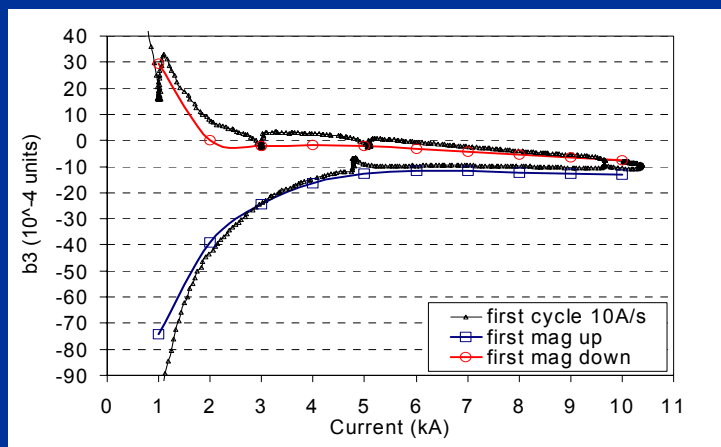
RD3c: Magnetic Measurements

Central harmonics

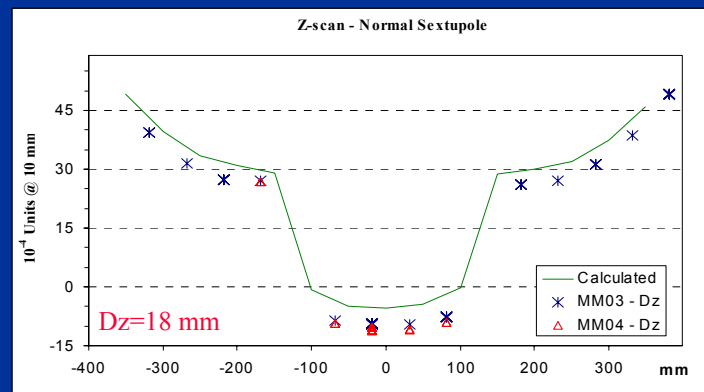
Normal	calculated	measured
$b_3 (10^{-4})$	-5.44	-10.39
$b_5 (10^{-4})$	-0.24	-0.02
$b_7 (10^{-4})$	0.58	0.61
$b_9 (10^{-4})$	<0.01	<0.01

$I_{op}=10$ kA, $R_{ref}=10$ mm

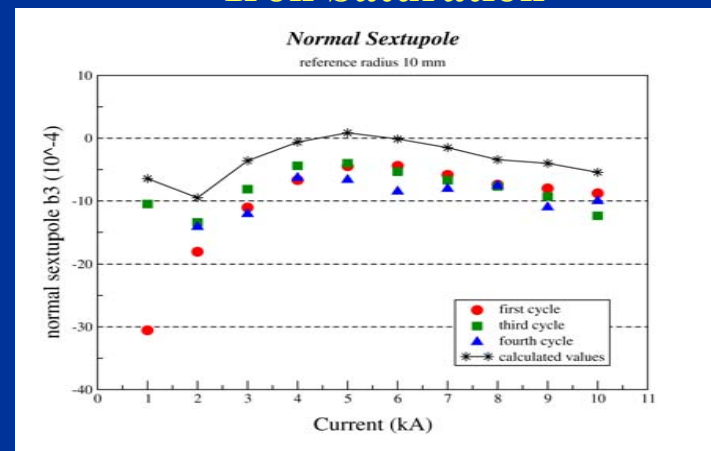
Magnetization – Eddy Currents



End-Field



Iron Saturation



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RD3c: Problem Summary

- “Stick-slip training” stalled above 8kA:
 - Magnet even “forgets” previous ramp.
- Quench training stalled 2kA (25%) above where “stick-slip training” stopped.
- Large hysteresis
- 5-unit geometric sextupole offset.
- Large a2 (common-coil).
- Unexpected b2 (with hysteresis).

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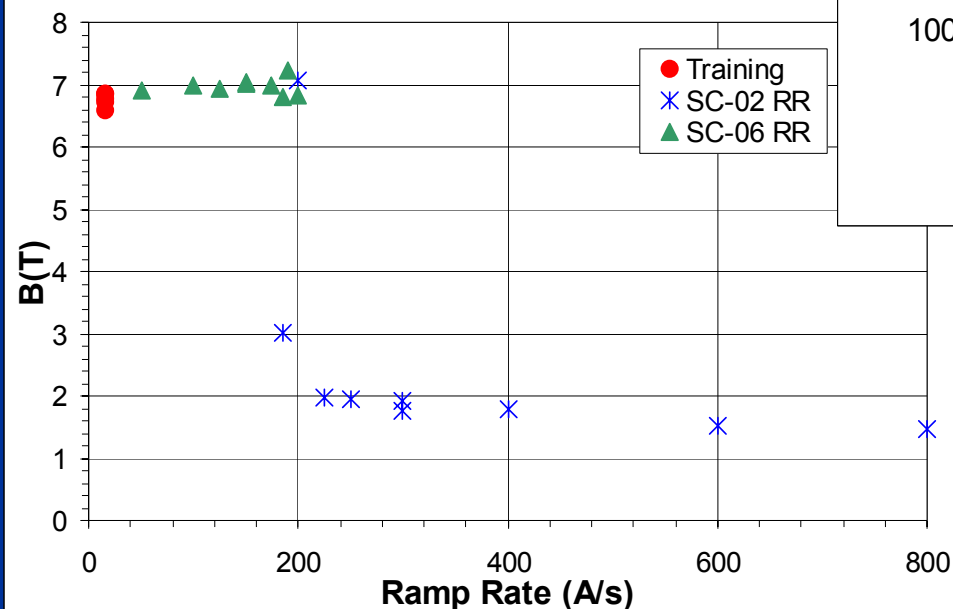


SM-03

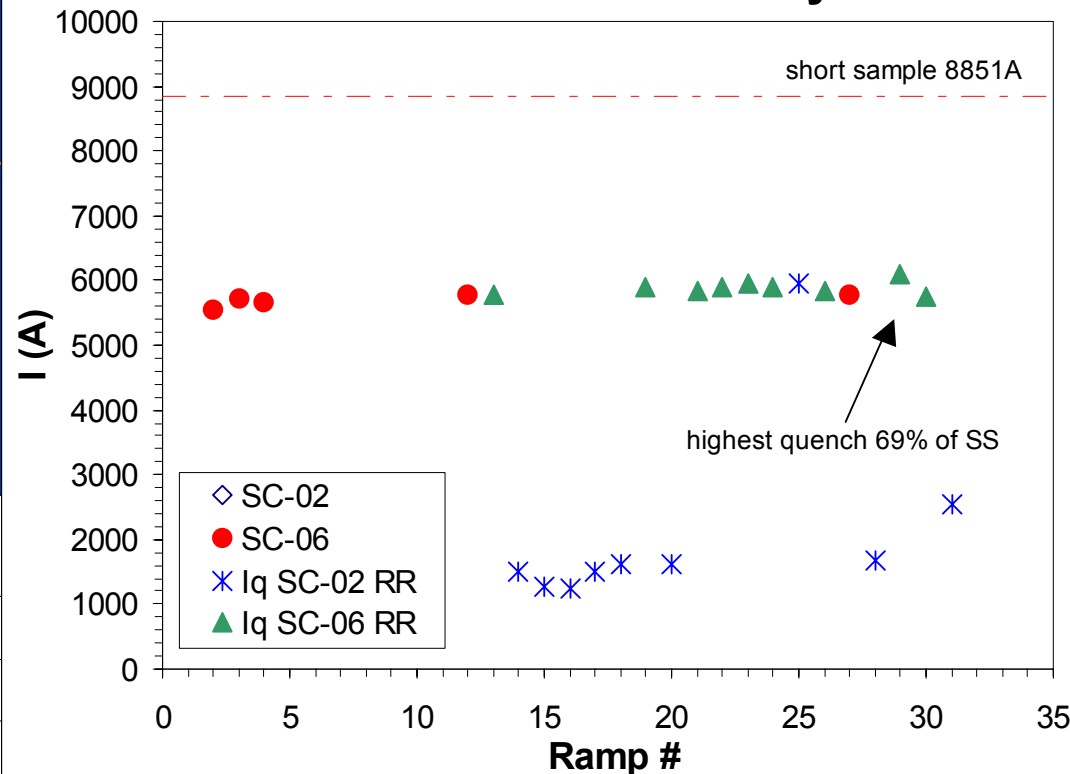
Magnet Performance:

- 7T (65% of SS-limit)
- Small (6%) training effect.
- Tiny (2%) ramp-rate hump.

SM-03 Ramp Rate Sensitivity



SM-03 Quench History



Conductor/splice performance:

- $RRR = 180$
- New amplifiers work well.
- $0.2 < R_{splice} < 0.3$ nOhm.



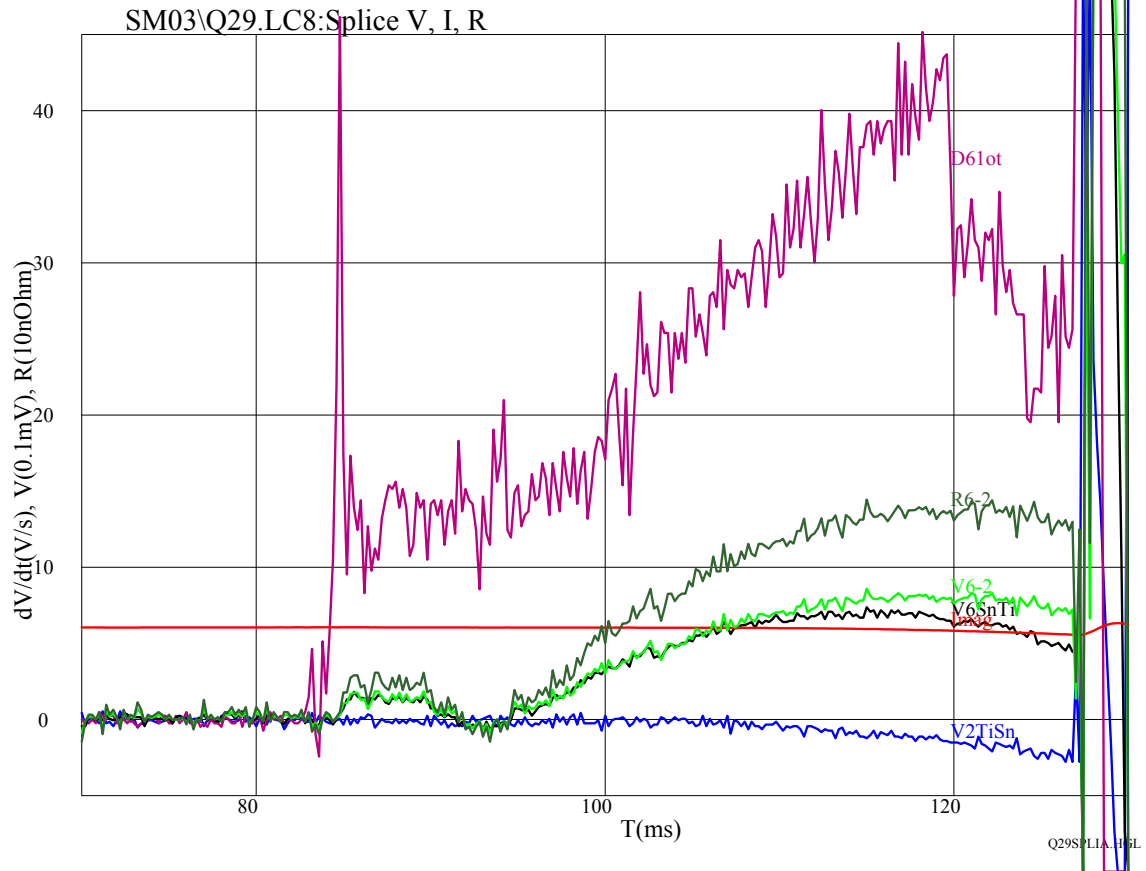
SM-03

Quench initiation:

- No fast motion!
- Intense, short start.
- Outer turn
- Not the splice.

Propagation:

- Into nearby splice.
- Temporary splice fallback??
- Rapid heating of Q-origin.
- Slow splice recession as current falls.



Conclusions:

- Splices: low heating, well cooled.
- Nb₃Sn damaged 5-10 mm from splice.

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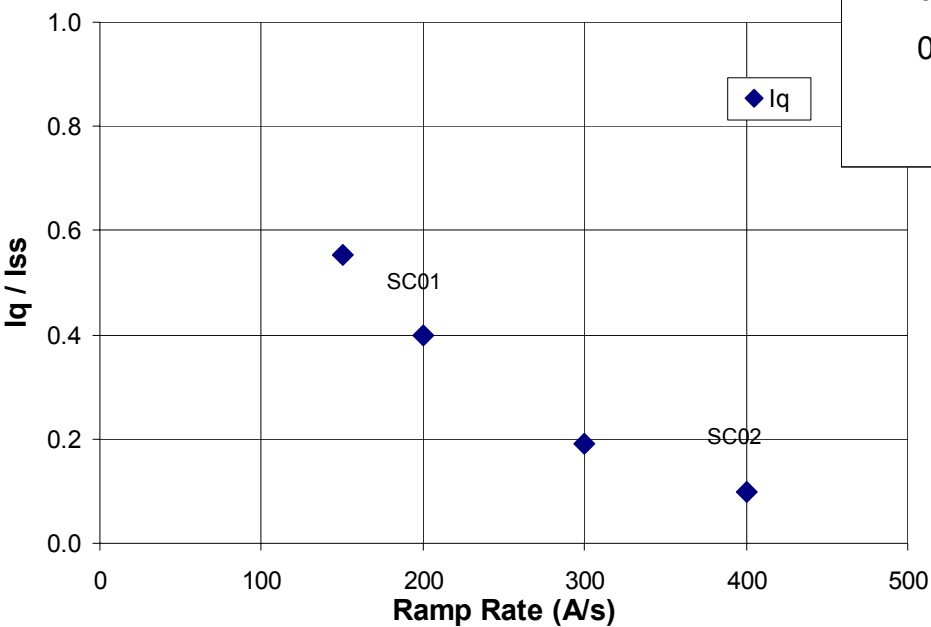


NMR

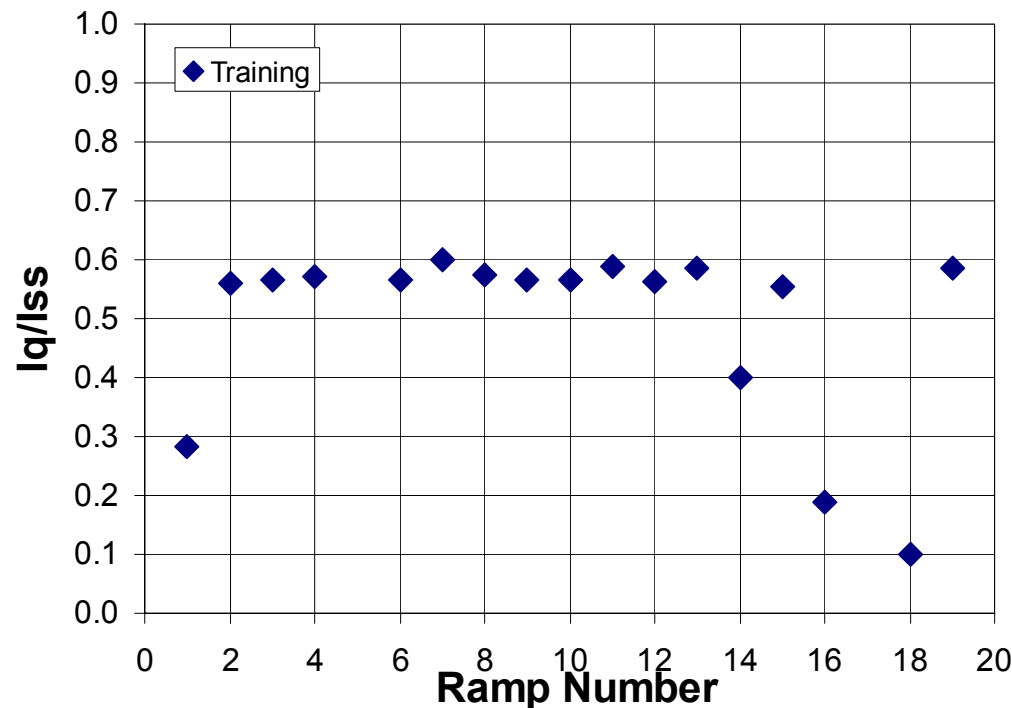
Magnet Performance:

- 7T (61% of I_{ss})
- No training effect.
- No ramp-rate hump.

NMR Ramp Rate Studies



NMR Quench History



Conductor/splice performance:

- $RRR = 5.6$
- New amplifiers work well.
- $0.2 < R_{splice} < 0.3$ nOhm.

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Quench initiation:

- Outside of splice.
- Many fast motions.
- All but 1st in SC-12.

Propagation:

- ~50% into nearby splice in ~1 ms.
- Maximum splice temperature after quenching: 40K.

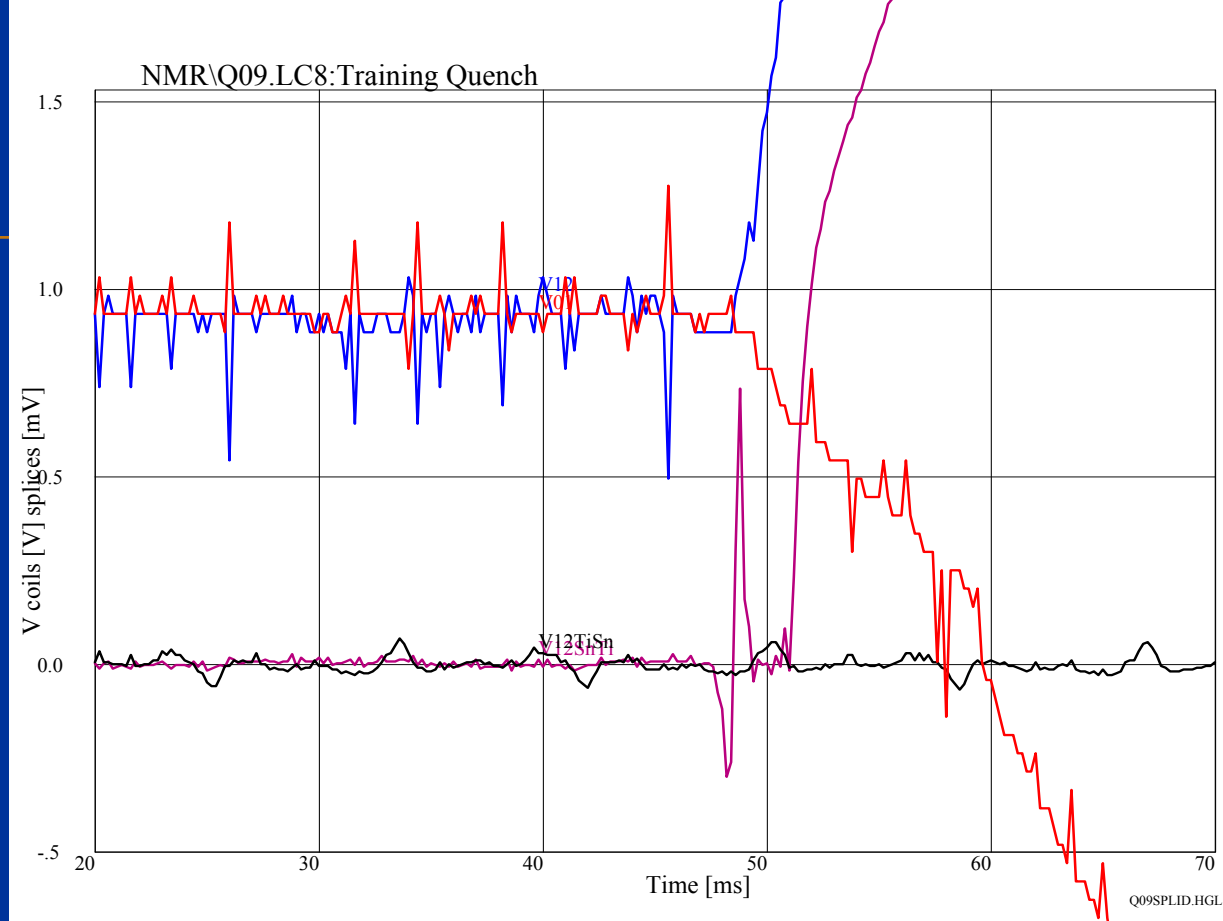


Conclusions:

- Splices: low heating, well cooled, but moving.
- ???

Conductor movement:

- Slipping at the SC01/SC12 interface (none at the other two coil interfaces).
- Some splice slips (1st observed).
- Gradual coil unloading started at ~80% of I_{quench} .



Conclusions:

- Needs faster DAQ working again.
- Splices: low heating, well cooled, but moving.
- ???



Summary

- Splice locale problems:
 - D20, SM02, SM03, NMR.
- Repetitive Conductor motion:
 - D20, Rd3c, NMR.
- Hysteresis:
 - D20, RD3c.
- Conductor Control:
 - RRR: RD3a
 - D_{eff} asymmetry: D20, RD3c.

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Future Improvements:

- R_{splice} Measurements:
 - More upgraded V_{splice} amplifiers.
- Conductor motion:
 - Quieter PS & environment.
 - Better localization (more chns, motion antennas).
 - Small prestress/training magnet study.
- D_{eff} & RRR problems:
 - Conductor improvements.
 - Better mfg & reaction Q-C.